CALIFORNIA PATH PROGRAM
INSTITUTE OF TRANSPORTATION STUDIES
UNIVERSITY OF CALIFORNIA, BERKELEY

A Comparable Systems Analysis of San Francisco's BART: Lessons for Automated Highway Systems

Mark D. Hickman
California PATH*

California PATH Working Paper
UCB-ITS-PWP-94-17

This work was performed as part of the California PATH Program of the University of California, in cooperation with the State of California Business, Transportation, and Housing Agency, Department of Transportation; and the United States Department of Transportation, Federal Highway Administration.

December 1994
ISSN

* Address: Institute of Transportation Studies, University of California, Berkeley, Richmond Field Station, Bldg. 452, 1357 S. 46th Street, Richmond, CA 94804-4698. Telephone: (510) 231-5644.

Acknowledgments

This study was completed as part of the FHWA-sponsored Precursor Systems Analysis for Automated Highway Systems. The financial support of the FHWA is appreciated. The author also recognizes Steven Shladover at PATH, who provided oversight for the research described in this paper. Other individuals also contributed valuable comments, including Stein Weissenberger at PATH, Loren Bonderson and Herb Hall at Delco, and Fred Mangarelli and Amy Cochran at Hughes.

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Abstract

This study examines the lessons to be learned from the experience of the San Francisco Bay Area Rapid Transit (BART) system, particularly as applied to the growing research on automated highway systems (AHS). By examining the technical and non-technical issues surrounding the development and implementation of BART in the 1960's and 1970's, the insights gained may be applied to future research and ultimate deployment of AHS. The first section of the report briefly motivates the analogy of BART by comparing some of the technical and non-technical performance factors surrounding both AHS and BART. Several pertinent technical and non-technical issues surrounding BART are described in more detail, emphasizing the decision-making that went in to BART's development, testing, and the beginning of revenue service. A short list of key issues is pursued in detail based on the most relevant and comparable areas of AHS and BART. On the technical side, the issues of safety, reliability, and maintenance were identified and investigated. It appears that sound system engineering principles were not applied in the BART case, and specific recommendations for improving this practice for AHS are described. In addition, the non-technical issues of political pressure and loss of public confidence are also investigated. In this case, these pressures have severely hindered BART from achieving its full potential. The insights from the BART experience are directed toward improving the planning, design, development and ultimate deployment of AHS.

Keywords: automated highway systems, public transit, system engineering, system integration, technology assessment

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Executive Summary

Introduction

This research was conducted as part of a recent Federal Highway Administration (FHWA) Broad Agency Announcement (BAA). The FHWA commissioned a precursor systems analysis regarding the technical and non-technical issues surrounding automated highway systems (AHS). As a part of that research, an analysis of comparable technical systems was performed to summarize the technical insight and lessons learned from these experiences. By examining recent experience with other highly advanced technologies, we may be able to avoid the mistakes of the past and also learn how better decisions can be made for the development and deployment of AHS.

The San Francisco Bay Area Rapid Transit (BART) system was one of three systems chosen by the Delco team for comparison with automated highway systems (AHS). There are a number of reasons why the experience at BART may offer some lessons for the development of AHS. First, the development of BART, like AHS, relied heavily on newer technologies for vehicle control and vehicle design, with the goal of automating train movements and other car-borne functions. Second, as a result of the high degree of automation, there is considerable concern for traveler and vehicle safety and system reliability in both BART and AHS. Third, both systems represent significant innovation in passenger transportation. As such, BART incurred a high level of public scrutiny, particularly as the system was to be used by a broad spectrum of travelers. Finally, the history of BART's development was dotted with political and financial issues that typically follow large transportation investments (such as AHS). For these reasons, the BART experience was examined more closely.

Methodology

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Based on the above criteria, we examined the history of the BART system to find out any lessons that the BART experience could have for the development of an AHS. Our methodology included conducting a literature review and interviews investigating the history and experience of BART's development (1950's and 60's) and early implementation (early to mid-1970's). From this review, we classified BART issues into technical and non-technical areas, relating these to the more prominent concerns with an AHS. Finally, based on the positive and negative experiences from BART's history, we developed recommendations for AHS development.

Technical Issues

There are several technical issues that marked the planning and development work for the BART system that have implications for AHS. First, like AHS, BART was designed with an interest in a high degree of technical sophistication. System operation includes automated headway and speed control and significant innovation in vehicle detection, communications, and car design. Second, this emphasis on new technology resulted in functional, rather than design, specifications, and put greater pressure on effective system testing and quality assurance. Unfortunately, in the BART experience, there was inadequate effort to ensure proper system integration and reliable performance. Third, the high degree of automation of BART operations required a detailed investigation of the system safety and reliability. However, it appears that system safety, reliability, and integration were not adequately addressed in this phase of the BART project, as significant safety and system reliability problems emerged in pre-revenue testing.

Other aspects of automated operation had impacts on the technical performance of BART. System operation relied heavily on automated control of trains in both normal and degraded modes of service. However, service did not meet the original expectations, largely due to severe limitations on both the automated and human operator capabilities in both normal operations and in degraded service conditions. Finally, the lack of system integration and component specification resulted in significant maintenance requirements, which were not anticipated in the planning for BART.

Non-technical Issues

There were a number of non-technical issues that affected BART that may also come to bear on AHS development. First, there were high expectations among transportation planners, politicians and the public at large that BART would be a panacea to problems of congestion and urban sprawl in the Bay Area. In spite of the capabilities of new technology, these goals were never achieved. Second, there was considerable sharing of responsibilities between the public and private sector in the BART project development. The responsibility for project management, design and construction was given to a private contractor, while public agency oversight of the development was minimal. This resulted in ambiguous roles between the public and private sector, with little accountability to the public.

In addition, there was considerable political pressure for BART to begin revenue service before the systems had been adequately tested. As a result, there were several well-publicized accidents and reliability problems in early revenue service. Fourth, demand for BART has been well below that which was predicted, resulting in lower benefits from the system and significant financial problems since opening for revenue service in 1972. Finally, the early reliability problems, accidents, and financial problems have resulted in a loss of confidence of the public in the management and operation of BART. These types of non-technical issues may also be faced by AHS during its development and early implementation.

Conclusions and Summary of Recommendations

The experience of the San Francisco BART system offers a number of important insights into the application of new technologies to the field of passenger transportation. These lessons reflect the process of technology development and management with BART that may also be experienced in the development of automated highway systems. From these observations of the development of BART, we have made several recommendations for developers of AHS:

1. In the development and procurement of AHS technologies, a competent and independent technical review team should be retained in each phase of the technical development and testing of the system.

2. AHS development should include both safety and systems engineering functions from the earliest part of system planning, design and development.

3. AHS specifications should include a strong emphasis on the design issues associated with service degradation, including equipment malfunctions in the vehicle, at the wayside, and in the infrastructure. In addition, these systems must be sensitive to the information provided to drivers during automatic operation and especially during degraded service conditions. Human factors research should emphasize the driver's response to information especially in degraded service or emergency situations.

4. AHS specifications and standards must carefully balance the needs for technical innovation with the need for more specific design criteria to assure a safe and reliable system.

5. Sufficient time in the AHS development process must be left for product testing and quality control. This involves allowing ample time for suppliers to debug new technical sub-systems, as well as time and resources to test and debug the fully-integrated AHS on site before beginning operation.

6. The highest priority must be given to safety and reliability in pre-service testing. Safety issues should be given highest priority in determining the readiness of an AHS system before start of service.

7. Maintenance issues should also be included early in the planning stages for an AHS, focusing on long-term maintenance requirements. For both vehicle- and infrastructure-based components, these requirements include maintenance equipment to identify and repair failures, common information systems, and clearly-defined procedures for addressing scheduled and unscheduled maintenance needs.

8. Technical personnel should maintain high visibility in AHS decision-making throughout the development process. Administrative and management boards should include staff with a high degree of technical competence in AHS.

9. As much as system design will allow, AHS projects should take advantage of incremental deployment. This may imply that an automated highway be deployed in a small corridor initially, allowing for system expansion to other corridors in the near future. The selection of an initial corridor should be based at least in part on the ability of that corridor to demonstrate significant first user benefits.

10. AHS development should include an aggressive and honest public information effort. This should include open public forums to discuss system planning and development and, as much as politically feasible, candid discussion of problems with development and deployment.

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1 INTRODUCTION

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This report summarizes PATH's analysis of the San Francisco Bay Area Rapid Transit (BART) system as part of a comparable systems analysis of automated highway systems. This first section provides an initial motivation to the investigation of BART, based on several performance factors and issues where BART compares most easily with AHS. Section 2 describes a preliminary investigation of the key technical and non-technical issues surrounding BART's development and operation, and draws some conclusions regarding their applicability to AHS. The final section describes a detailed analysis of several key technical and non-technical issues, specifically making recommendations for AHS based on the BART experience. [Throughout this report, BART is used to refer to the rail transit network and its operation. The organization which runs the transit system is the Bay Area Rapid Transit District, or BARTD.]

There are several performance factors and issues that suggest that rapid transit systems, and particularly the Bay Area Rapid Transit (BART) system in the San Francisco Bay Area, may be reasonably comparable to an automated highway system. The suggested comparison addresses the following performance factors:

1. **Interaction with the general public**. BART represents a comparable transportation system, in which some segment of the urban public is given a new transportation alternative, intended to reduce freeway congestion and improve travel times. At present, BART accommodates nearly 260,000 trips per day in the Bay Area. As a new transportation alternative, automated highway systems have similar goals.

2. **Degree of intelligence incorporated**. BART train operation, control, and supervision are all fully automated. Train movements in the network are under full control of a central management center using a reasonably sophisticated signal and communications system. In an automated highway system, a high degree of intelligence will also be incorporated.

3. **Operation with a severe safety constraint**. There were considerable safety issues associated with full automation of BART: automated and manual train control in accident or other emergency situations, hazards associated with the many car-borne components and sub-systems, safety of passengers in stations, potential failures of both train and central control systems, and other infrastructure failures. There are also considerable safety implications with automated vehicle control with an AHS.

4. **Operation with a severe reliability constraint**. Under full automation, BART trains are under considerable reliability constraints: maintaining train schedules, interpreting speed commands, maintaining safe distances between trains, sensing exact location of trains in stations, and coordinating train movements at route junctions. The complexity of vehicle components and system integration will play a particularly strong role in determining the reliability of an AHS, as it has for BART.

5. **Environmental constraints**. BART represented a significant disruption to local communities in the Bay Area. Initially, the project involved land acquisition for the track right-of-way. In addition, BART trains generate considerable noise for local communities in the aerial and at-grade sections of track, as well as reducing the visual aesthetics of these neighborhoods. The environmental impacts of an AHS are still being investigated, but will ultimately have significant impact on the system design and implementation.

6. **Large number of diverse sub-systems**. Many subsystems are required for BART, including car-borne, wayside, infrastructure, and centrally controlled systems. These include sub-systems for train propulsion, automatic train operation, train detection, signaling, a fixed infrastructure and right-of-way, and a central computerized control system. With the comparable infrastructure and vehicle-borne systems, AHS also will involve a large system of diverse technical components.

7. **Operation over a geographically wide area**. BART crosses a number of diverse geographic areas, including crossing the San Francisco Bay. Perhaps more importantly, BART operations cross a number of political jurisdictions, requiring considerable political consensus-building and public support. As a result, BART is growing incrementally, with specific corridors being added as funds and support become available. An AHS, as well, may ultimately operate over a broad range of geographic areas and may require large contiguous sections to be feasible.

8. **Similar failure modes**. Failures in the automatic train control and train detection systems have resulted in several well-publicized accidents on BART. In addition, equipment and sub-system failures require the removal of trains from service and associated disruptions in network performance. Vehicle or infrastructure system failures are also present for an AHS, and represent significant constraints on the public perception of AHS.

9. **Outage time constraints**. Safe and prompt response to service disruptions and system failures are necessary on BART. Although fail-safe principles apply to most system outages, continued operations under degraded service conditions is critical to the system function. This need was demonstrated most obviously in the first few years of revenue service, as system problems were discovered and addressed. For an AHS, the operation will no doubt also include system failures and degradation, and AHS operation in these periods must also be critically examined.

Based on these performance factors, there appears to be substantial value to examining the development and operating experience on BART to derive insights for AHS development and deployment.

2 PRELIMINARY DISCUSSION OF BART ISSUES

An initial review of the literature with the planning, development, and operation of the BART system was conducted. From this review, a set of salient issues regarding the BART system are particularly relevant for the continuing development and deployment of automated highway systems. This section below summarizes these issues and identifies critical areas for further analysis, discussed in section 3.

There is a wealth of literature regarding the planning, development, and operation of the BART system. One could argue that BART is perhaps the most studied mass transit project in the United States, considering the very high level of scrutiny of the system during the 1970's and into the early 1980's. This literature suggests a number of important issues that have surfaced in the development and operation of BART that may be relevant for future technology options in transportation, including AHS. Below we highlight the relevant issues associated with BART and comment on their relevance to AHS, organized into both technical and non-technical areas.

2.1 Technical Issues

1. Level of technical sophistication. The technology chosen for BART was seen as the state of the art in the 1950's. BART represented a significant opportunity to capitalize on new technologies in public transit. In order to lure travelers to the system, planners envisioned a high level of service, with headways of 90 seconds between trains and top speeds of 80 miles per hour. One technology proposed to reach these goals on BART was an automatic train control (ATC) system. At the time, there was little opposition to this new system, although it was untested and unproven at the time when the choice of technology was made. BART was seen as an opportunity to bring transit train control systems into the 20th century, using new and more sophisticated vehicle detection, communication, and train control technologies. Similar choices about the level of sophistication of vehicle and roadway technologies are pending for AHS.

2. Level of technical verification and testing. Having decided on advanced train monitoring and control technologies, both BARTD and the prime contractor (a team of Parsons-Brinckerhoff, Tudor, and Bechtel, or PBTB) developed specifications for these automatic systems. However, contracts to develop the technical systems were not always awarded to contractors with appropriately tested and proven technologies. As an example, the ATC contract was awarded to the lowest bidder (Westinghouse Electric) based on a system that had not been previously tested or demonstrated. In addition, prior to revenue service, each car-borne and wayside system was to undergo significant product testing and quality assurance. These quality standards, however, were not rigorously maintained, largely due to significant political pressure to bring BART into revenue service as quickly as possible. Similar standards and specifications of AHS systems will be developed in the near future, and there is need for a rigorous program of verification and testing for the technical performance of AHS systems.

3. Consideration of safety and reliability. In the initial act creating BARTD, the California Public Utilities Commission (CPUC) was given authority to monitor the safety of BART operations. The CPUC had little experience with transit systems, however, and provided very little oversight during the initial years of system development. In general, there were few safety standards included in the original system specifications. Moreover, PBTB and BARTD did not have any safety, reliability, or systems engineers on the project until the early 1970's as the project moved into pre-revenue operation. The need for this capability, however, was evidenced by a large number of problems which surfaced during initial system testing. These problems included a large number of safety issues, including unintended station run-throughs at 50 mph, large gaps between BART cars and platforms, inadequate hand-holds for standees in the cars, and a lack of information displays for the train operator to provide service in degraded service conditions. Also, as noted above, inadequate attention was paid to product quality, resulting in considerable reliability problems with the ATC system and the cars during both pre-revenue testing and in revenue service. As with AHS, safety and reliability aspects of the automatic system will be critical to its successful deployment.

4. Other shortcomings in technical performance. BART was originally expected to operate on 90-second headways through San Francisco and Oakland, with peak operating speeds of 80 mph on some line segments. These objectives have not been met, largely due to safety problems with the ATC system, train and car reliability problems, lower than expected acceleration and deceleration rates, and considerable control delays at track junctions (i.e., the Oakland Wye) and at track endpoints (most notably Daly City). Moreover, BART operations have shown little tolerance for faults in the system. First, as mentioned above, there was little consideration in the train cab design for information to be supplied to the train operator during normal or degraded service (e.g., location of train system malfunctions, speed limits, block occupancies, etc.). Second, there were extreme limitations on manual operation in degraded mode, restricting trains to speeds below 25 mph and requiring significantly longer block clearances (i.e., headways) for trains. These problems caused significant disruptions to service, especially during the first several years of revenue service. This may hold some lessons about developing reasonable expectations of AHS service both in normal operation and in degraded service conditions.

5. Maintenance requirements. BART's experience has reinforced the supposition that higher technology leads to much higher maintenance costs. Initially, many of the problems normally attributed to maintenance were in fact due to poor workmanship and quality control of the car systems from the supplier. At the same time, BARTD lacked the know-how on their maintenance staff to deal with train and car problems, resulting in high dependence on the car supplier. In addition, a number of studies have compared the maintenance experience at BART with other rail transit systems with a lower degree of automation. From this perspective, the experience at BARTD strongly suggests that the operating personnel and expenditures saved by employing an automated system are less than those now required to maintain the system. As AHS systems are likely to require significant maintenance of both infrastructure and vehicles, these requirements should be identified and addressed.

2.2 Non-technical Issues

1. Level of expectations for the project. At its inception, the BART system was intended to be a panacea to the problems of urban sprawl, decentralized commercial activity, and traffic congestion. Planners believed that this new transit system would focus development in the urban core areas of Oakland and San Francisco. This effect would be enhanced by alleviating traffic congestion in the Bay Area, thereby reducing the cost of commuting to these urban areas. As significant research by BARTD staff has reported, BART has had little impact on commercial activity in Oakland and San Francisco and has done little to alleviate traffic congestion. There are similar high expectations for an AHS system, which should be examined carefully to determine whether these expectations are credible.

2. Public and private responsibilities in project development. BARTD selected a single contractor, PBTB, for both the system design and the construction management. In this regard, the contractor team was awarded a cost plus fees contract. PBTB was answerable directly to the BARTD board of directors, leaving little oversight from BARTD staff to manage PBTB's costs or engineering practices. Moreover, there was little technical experience in rail transit systems among personnel at BARTD, leaving the lion's share of the technical oversight for the project with PBTB. PBTB also controlled contract management for all sub-contractors, many of whom were traditional defense contractors with little or no experience in transit systems. Clearly, the BART project blurred the roles of both public agencies and private firms. AHS will likely bring

both public and private interests into project development, and responsibilities should be deliberately and clearly defined.

3. <u>Political pressure to bring project into revenue service.</u> Like most big public construction projects, BART ran over budget and opened for revenue service much later than expected. Delays resulted from a wide variety of causes, including construction problems, contracting negotiations and disputes, quality problems in pre-revenue testing, and arrangements for additional construction funding. Significant political pressure, however, brought the system into revenue service well before the full system was operable and before the system had undergone sufficient testing of technical components. As a result, significant degradations in service and several well-publicized accidents marred the first several years of revenue operation. AHS will also come under significant political pressure to begin operation which must be dealt with appropriately.

4. <u>Market prediction.</u> As with many rail transit projects opening up over the last 20 years, actual ridership on BART was much lower than the optimistic forecasts. Figures for 1975 generally show BART daily ridership on the order of 51% of the forecast value (133,000 actual versus 260,000 forecast). In BART's defense, however, many researchers focus on ridership trends and forecasts before the system had fully matured. Even today, however, ridership levels are lower than originally planned. Some reasons for this shortfall include: lack of rigor in the forecasting methods used in system planning, unanticipated growth in automobile ownership and continued low marginal costs of automobile use, poor station access, and public concerns for system reliability and safety. In this light, caution and discretion is necessary in predicting public acceptance and the demand for AHS.

5. <u>Loss of public confidence.</u> During the first several years of BART operation, there were significant delays and disruptions in service mostly due to problems with the ATC system and other car-borne and wayside systems. In addition, several accidents in both revenue and non-revenue service were attributed to system failures or poor operating procedures, resulting in significant negative publicity for BART. This led to a quick loss of public confidence in the safety and reliability of the BART system. This confidence was further shaken by significant financial problems in the first several years of revenue service. The public perception of BART has only slowly recovered from these initial setbacks. As with other high-technology systems, AHS will also face considerable early scrutiny of system performance, and how initial setbacks are handled may ultimately determine the success or failure of AHS.

From our initial list of issues, a number of areas were identified for further research that should provide additional insight into AHS. On the technical side, BART may offer some additional insight into appropriate techniques for technical systems specification, verification of system performance, and initial pre-deployment testing and quality assurance (Item 2 from the technical issues list). Given the potentially high complexity of the many systems involved in AHS, successful deployment depends critically on the ability to specify and test a highly reliable system. A related issue is the treatment of both system safety and reliability in the technical development and in system operation (Item 3 from the technical issues list). In addition, the level of effort required to maintain the automatic systems on BART (Item 5) is also investigated more thoroughly.

From the non-technical issues list, items 3 and 5 are pursued in greater detail, covering the response of BARTD to continued political pressure to bring the system into revenue service, coupled with the early loss of public confidence. Typically, as a public service, new technologies in transportation come under intense political pressure, as elected officials press for early photo opportunities and quick benefits to improve their political standing. The high expectations already placed on AHS ensure that the political process will have much bearing on the development and deployment of these systems. Our study of BART should offer some insight into ways of dealing with the political pressure without compromising the success of the system. Furthermore, in considering the early stages of AHS deployment, safeguards are necessary to avoid quick loss of public confidence. Close scrutiny of AHS operations is unavoidable, but lessons from BART may help avoid the erosion of public trust that may seriously hamper planned AHS projects.

3 DETAILED DISCUSSION OF BART ISSUES

Following the conclusions of the initial discussion, the following section discusses in greater detail the technical and non-technical issues of greatest interest. The first section discusses the technical issues of safety, reliability, and maintenance, while the second section details the non-technical issues of handling political pressure and the loss of public confidence.

3.1 Technical Issues

There are several key points to be made regarding the technical development of the BART system. However, before going into detail on the specific issues of safety, reliability, and maintenance, it is important to make some general observations about BART and the technical development process. During development of the technical systems in the 1960's, the role of BARTD was primarily managerial as opposed to technical, and intentionally so. PBTB, the prime contractor for system design, development, and construction, was responsible for system integration and technical oversight. It was not until the system went in to pre-revenue testing that many of the technical responsibilities began shifting from PBTB to BARTD. As the reader may note, many of the problems and pitfalls noted below fall in the gray area of technical responsibility between PBTB and BARTD, often during this period of time just before the system opened.

The delegation of virtually all of the technical development tasks to PBTB meant that there was little oversight or control by BARTD staff. This is considered by most researchers to have been the most significant error in the development of BART.[1] The primary problems with BART did not really stem from poor technical choices; rather, their root cause lies in poor project management and oversight on the part of BARTD. Many researchers have noted that up until the late 1960's, only one member of BARTD staff was an engineer, and he had served as a consultant to PBTB in some of their BART work prior to arriving at BARTD. Thus, there was little review of PBTB's technical work, either by BARTD or an independent review board, during the development process in the mid- to late-1960's. Such a review may have significantly improved the management of the technical development process.

> **Recommendation**: In the development and procurement of AHS technologies, a competent and <u>independent</u> technical review team should be retained in each phase of the technical development and testing of the system. In addition, the operating organization should hire technical personnel from the very early stages of project development.

There are several other characteristics of the technical development of BART that deserve mention. First, through the technical development process, BARTD and PBTB lacked any individuals or groups specifically assigned to the task of systems engineering. Such a group is responsible for integrating any number of complex subsystems into an integrated, operating unit. While such systems engineers are common in detailed aerospace technologies, they are relatively rare in the field of transportation. Such an organization would consider the integration of vehicle subsystems as well as the functions of wayside equipment and central control facilities. Due to the considerable development of new technical subsystems as a part of BART's development, a

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[1]See, for example, Burck (1975), p. 105; Profet (1973), pp. 124ff.; and Legislative Analyst (1972), pp. 51ff.

specific systems engineering function would have aided in system integration, in anticipating system hazards, and in responding to system problems.

Recommendation: In program development as well as in each field operational test and proposed implementation, a separate systems engineering function should be incorporated that integrates AHS subsystems for the vehicle, wayside, and infrastructure.

Second, PBTB chose to use *functional* rather than *design* specifications for the development of several technical subsystems. These specifications allow characterization of a system in terms of its function, rather than determining specific equipment or other detailed design standards. These functional specifications allow the greatest level of innovation by the system developer, since they can then meet the goal of the function using any appropriate technology, with a minimum of constraints on the design itself. In the BART experience, examples of liberties taken in design include development of a (novel) train control system, development of new car technology by an aerospace contractor, and a non-standard gauge and concrete ties for the track to improve ride stability. While this may allow considerable flexibility in system design, this type of specification makes it difficult to verify contractual obligations of each system contractor when the system does not perform as desired. This was most evident when BARTD entered litigation separately against Westinghouse and against Rohr over the issue of system specifications and the resulting contractual obligations.[2] In addition, the high degree of innovation in system design may also lead to difficulties in integrating various sub-systems.

Recommendation: As with other technically complex systems, AHS specifications and standards must carefully balance the needs for technical innovation with the need for more specific design criteria to assure a safe and reliable system.

3.1.1 Safety

During the first several years of operation, the BART system was plagued with safety problems. Many of these problems resulted not from operator error but rather were the result of faults in the technical systems. Several safety issues first emerged in pre-revenue testing, as many of the technical bugs were worked out of the system. This period of testing was short, and as the system was rushed into revenue service, safety problems received much greater publicity.[3]

The first major accident in revenue service occurred a mere three weeks after the system opened in 1972. According to the investigation by the Legislative Analyst,[4] the car-borne automatic train control (ATC) equipment failed to identify a speed command correctly, causing the train to speed past the Fremont station and crash at the end of the line. In January 1975, a non-revenue train had a fatal collision with a maintenance vehicle; the accident was blamed on the inability of the automatic train detection system to detect maintenance vehicles, even when they shared the right-of-way with service trains. A third serious accident in 1979 involved a train fire in the Transbay Tube, burning five of seven cars of the train. Further investigation revealed that the material from which the BART cars were manufactured was not sufficiently flame-retardant.

The incidents above raise specific concerns about the treatment of safety by BARTD and its prime technical contractor, PBTB, primarily because these problems were largely the result of technical error. It seems that the root causes of these safety problems at BART resulted from a

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[2]Office of Technology Assessment (1976b), p. 144; and Burck (1975), p. 105.

[3]Office of Technology Assessment (1976b), p. 8.

[4]Legislative Analyst (1972), pp. 25ff.

number of factors in the system development process.[5] The following suggests some of these factors and some of the lessons that can be learned about the treatment of safety in the technical development of AHS.

1. **Specification of safety requirements for system components**. The system specifications put forth by PBTB for each of the technical systems were primarily *functional* and not *design* specifications. In this way, the contractors responsible for each technical subsystem could have the greatest latitude in developing the technology, rather than being locked more rigidly into standards and existing technologies. However, this also meant that specific safety standards for each technology were basically non-existent: the technology for critical sub-systems (such as the ATC system) lacked widespread industry safety standards.[6]

   Recommendation: Regardless of the decision for functional or design specifications, safety and reliability requirements for system operation should be included directly.

2. **Hazard analysis of the system**. Since many of the sub-systems for use in BART were developed as new technology, it would have been helpful to have a systems engineering function to determine appropriate ways of integrating these sub-systems. One part of this systems engineering function would be a complete hazard analysis of the various system components and all of their possible modes of failure. Oddly, this kind of hazard analysis was performed on the car-borne and wayside ATC equipment in 1971, and identified several critical deficiencies in the system design, including the possibility of higher-than-expected speed commands on board the vehicle.[7] Unfortunately, PBTB had not investigated this matter further before the related accident in revenue service in 1972.[8]

   Recommendation: A critical function of an AHS systems engineering group should be a detailed hazard analysis of vehicle, wayside, and infrastructure systems. This hazard analysis must be performed as early in the design process as possible to allow easier revisions to the system design.

   Recommendation: Safety issues should be given highest priority in determining the readiness of an AHS system before start of service.

3. **Technical experience at BARTD and the CPUC**. The California Public Utilities Commission (CPUC) was given the responsibility for assuring safe operation of BART in BARTD's enabling legislation in 1957. However, PBTB controlled technical system specification and development up until the system opened for revenue service. Personnel at both BARTD and the CPUC during the 1960's and early 1970's had little experience with rapid transit systems or their associated technologies.[9] Both agents may have been aided by hiring technical personnel much earlier in the technical development process.

   Recommendation: A staff of technically competent safety engineers should be hired (or retained) to conduct independent safety analyses for an AHS system. This staff should be brought in to the AHS project development process as early as possible.

4. **Organizational treatment of safety within BARTD**. Up until April 1972, a few months before the system opened, safety engineering was included as a small organization within the

[5]Office of Technology Assessment (1976b), p. 85.
[6]Ibid., pp. 166-167.
[7]Crooks et al. (1971), pp. 169-170.
[8]Ibid., pp. 232-233; and Legislative Analyst (1972), pp. 27-28.
[9]Legislative Analyst (1972), pp. 37-45.

Operations department. This organization relied heavily on the technical expertise of the operations and maintenance personnel. In the view of several researchers, this did not allow a fair and independent safety review, since the operating personnel were under considerable political pressure to put the system into revenue service quickly.[10] In May of 1972, the safety group was moved to within the Finance department, creating a new Insurance and Safety organization that was at least independent of the political pressure but nonetheless distant from the technical expertise of operations and maintenance. In 1973, the group was moved up to the department level (the Insurance and Safety department), largely due to political pressure resulting from the revenue service accident and other well-publicized studies of system safety.[11] The technical competence of the safety group was still inadequate, leading BARTD to retain the Lawrence Berkeley Laboratory as safety consultants for several years after beginning revenue service.[12] It was not until July 1975 that an independent Safety Department was formed and given considerable responsibility for more technical safety issues.[13]

Recommendation: A safety engineering function should include staff members at the highest possible level within the project development team, who can effectively communicate safety concerns to project management. Again, safety issues should have highest priority in system development and in preparations for the start of service.

5. **Capabilities of a safety program**. Now that BART has been in operation for over twenty years, the safety organization has ultimately been given considerable responsibility and broad authority to improve safety within BARTD. The responsibilities of the BART safety program now, in full operations, may be transferable to an AHS safety organization. These tasks include:[14]

   - Setting reasonable safety goals and objectives for BARTD
   - Informing BARTD management of safety status, problems, and improvements
   - Participating in the planning and review process for system design, construction, reliability, maintenance, and personnel training
   - Review of engineering tests to ensure compliance to safety requirements
   - Monitoring and inspection of system operation
   - Conducting hazard analyses to identify and mitigate safety risks
   - Analyzing operating rules, procedures and practices to limit exposure to hazardous situations
   - Collecting and reviewing historical information on hazards, system failures, and accidents
   - Investigating system failures, mishaps, and accidents
   - Ensuring operability of hazard detection and warning systems
   - Ensuring compliance with regulatory agencies
   - Organizing and coordinating safety programs within BARTD
   - Conducting scheduled and unscheduled disaster and emergency exercises and drills

3.1.2 Reliability

Because many of the sub-systems in BART relied on new technology, it is of interest to examine how reliability was treated in system development and early deployment. The facts of the

[10] Ibid., pp. 43-45.
[11] Ibid.
[12] Legislative Analyst (1974), pp. 11ff.
[13] Legislative Analyst (1977), pp. 20-21.
[14] Taken from BARTD Safety Department (1978), pp. 15-16.

BART experience are clear: in its early years of deployment, the system was racked with problems. As late as 1975, three years after opening for service, an average of 40% of BART cars were out of service on a given day because of failed components. Car-borne system failures occurred very often in revenue service, seriously degrading performance not only for a given train but also across the entire BART network. Failures in the wayside ATC system also caused considerable delays. In time, however, BART has been able to recover from many of these early reliability problems, but not without considerable public dismay over the system performance.

AHS, because it represents an entirely new technology, has very severe reliability constraints associated with successful deployment. In contrast with BART, however, an implementation of AHS may come under significantly greater pressure to ensure a high level of safety and reliability in early operation. Also, AHS may not be so fortunate for a long "grace period" to work out the bugs in the system; perhaps today's public is less forgiving and patient than before. To this end, the following identifies some issues in system design and development that may provide learning experiences from BART.

1. **Design for "graceful decay"**. BART was intended and ultimately achieved its goal of completely automated train operation, even under degraded service conditions. However, during the first several years of operation, procedures for degraded service modes yielded significant disruptions in service. Statistics from the first three years of operation show that passengers had to be off-loaded for one out of every four equipment failures, a measure at least seven times worse than a peer group of rail transit systems. Moreover, during any car-borne sub-system failure, "fail-safe" procedures were applied; in almost all cases, this implied a full stop of the given train, after which the train was limited to a maximum speed of 25 mph. Since there are few yards or sidings on the BART system, these trains would often continue over a significant portion of the network at this reduced speed. The frequent stops and speed restrictions resulted in serious delays in service that propagated through the system.[15]

   Recommendation: Consideration of automated systems should focus on a graceful decay for degraded service modes. System specifications should focus on the design issues associated with service degradation, including equipment malfunctions in the vehicle, at the wayside, and in the infrastructure.

2. **Design for human interaction**. As originally designed, the train operator is responsible for train operation only in the case of a major service disruption or emergency. However, because the ATC system was not fully operational when BART opened for revenue service and because service disruptions occurred frequently, the operator played a more significant role during the first couple of years of operation. This role was impeded by a cab design which assumed a much more passive role of the operator: there were no information displays in the train cab for the operator to know the intended vehicle speed or information on sub-system failures within that train. As a result, operators often used line-of-sight rules for train operation or held trains in a station for a long time to locate car problems. This was a serious design error that led to substantial train delays in early revenue service. It was several years after beginning operation before the cab interfaces were upgraded.[16]

   Recommendation: Clearly, AHS must be sensitive to the information provided to drivers during automatic operation and especially during degraded service conditions. Human factors research should emphasize the driver's response to information especially in degraded service or emergency situations.

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[15]Brumberger (1980), p. IV-14.
[16]Ibid., p. II-7 and p. III-3; and Office of Technology Assessment (1976b), p. 157.

3. **System specification and development**. With some federal financial assistance, PBTB developed a test track to test alternative system configurations. The track ultimately had two purposes: 1) to allow prospective system suppliers to test their products; and, 2) to assist BARTD and PBTB in developing specifications for each of the required sub-systems.[17] Many suppliers participated in the testing program. Moreover, PBTB often incorporated the abilities of several products tested on the track in developing the functional specifications for new sub-systems. This testing program was very successful, considering the lack of existing research and development on these systems nationally at that time.[18]

   In deciding on contract awards, however, the testing experience was largely ignored.[19] Since the specifications were functional, the actual design of each sub-system was left to each contractor to define. Moreover, contract award criteria were independent of whether vendors had (successfully) demonstrated their product either on the test track or in any other application. As a result, many of the contracts were awarded to suppliers with little experience and / or no proven product. For example, the contract to supply rail cars was given to a supplier (Rohr) with no experience in rail transit, and the ATC system contract was awarded (to Westinghouse) in spite of the fact their proposed system had never been tested and no prototype existed.

   Recommendation: As much as possible, each AHS operational test site should be flexible to allow various manufacturers to test a variety of technologies. In selecting system suppliers, technical experience, proven technology, and test results should be given considerable weight in the selection criteria.

4. **Pre-revenue system testing and quality assurance**. BARTD had no internal quality control organization for the delivered systems.[20] As a result, operating and maintenance personnel at BARTD relied heavily on PBTB for early product testing and quality control. At the same time, political forces were applying considerable pressure on PBTB to bring the system into revenue operation; construction delays had already pushed back the opening for revenue service from 1969 to 1972. For this reason, testing and quality control functions were rushed, leaving considerable doubt regarding the effectiveness of the test procedures.[21] According to one report, less than half of the rolling stock had been subject to adequate yard departure testing, and none of the cars had undergone complete ATC system tests, prior to revenue service.[22] This inadequacy of system testing also had significant repercussions for the maintenance function at BARTD, as noted below.

   Recommendation: Sufficient time in the AHS development process must be left for product testing and quality control. This involves allowing ample time for suppliers to debug new technical sub-systems, as well as time and resources to test and debug the fully-integrated AHS on site before beginning operation.

3.1.3 Maintenance

Maintenance was the responsibility of BARTD once the various contractors began delivering each of the sub-systems. The Maintenance organization, within BARTD's Operations department, was responsible for checking car-borne systems upon arrival of the car at the yards.

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[17]Office of Technology Assessment (1976b), p. 141.
[18]Ibid., p. 152.
[19]Ibid.
[20]Lancaster and Teske (1973), p. 6.
[21]Office of Technology Assessment (1976b), p. 149.
[22]Legislative Analyst (1972), p. 69.

As noted above, the maintenance department relied heavily on PBTB to supervise these testing procedures.[23] Once revenue service began, BARTD alone was responsible for approving trains for release into revenue service each day. Because many of the delivered sub-systems had not been adequately tested for quality assurance, the maintenance function faced a considerable workload once the system entered revenue service. Anywhere from 30% to 60% of the cars were in the shop on a given day, and about 25% of the cars were brought into the shops three or more times with the same problem.[24]

Several factors influenced the planning and management of maintenance at BARTD that can offer similar insights for AHS:

1. **Design for maintenance**. In terms of product design, PBTB took a novel approach to specifications by including reliability, maintainability, and availability (RMA) specifications directly. Despite this approach, a number of contractors did not adequately consider product failures and maintenance requirements in designing their systems. For the cars, critical train control systems were located in very troublesome positions on the car, requiring significant time to repair or replace. The car manufacturer also did not adequately consider some of the environmental hazards of rail operations; for example, several critical components were mounted on the undercarriage, where there is considerable wear and tear in normal operation.[25] On the other hand, some components were a little too accessible. For example, the emergency door release equipment was placed just below a passenger seat, and attached only with velcro. From that viewpoint, a passenger might accidentally (or deliberately) open the doors while the train was in motion.[26] Such problems required modification of the location of car components.

   Recommendation: RMA specifications should be used for any AHS implementation, including explicit MTBF and MTTR requirements. These requirements should be specified for both vehicle and wayside equipment, ensuring that parts are easily accessible and that component trouble-shooting requires minimal effort, both on board the vehicle and in the automated lane segments.

2. **Maintenance information**. Initially, BARTD maintenance personnel were very dependent on PBTB and its subcontractors. This occurred largely because the system specifications had been developed by PBTB and ultimate product designs were approved most often without adequate oversight by BARTD personnel.[27] Another significant problem with BARTD's maintenance efforts in the early years can be attributed to a lack of information on the built systems: significant discrepancies were often noted between car-borne systems as delivered and the blueprints on hand at BARTD. Information was inadequate, placing additional dependence on the contractors to assist in the maintenance.[28] The maintenance effort was also poorly implemented within BARTD: there was initially no consistent information reporting format to identify problems on cars as they were brought to the shops, making it difficult to know the type and severity of the problem.[29]

   Recommendation: AHS system operators should develop substantial maintenance capabilities in house during system development. Because of the large number of diverse sub-systems

[23]Profet (1973), pp. 78ff.
[24]Legislative Analyst (1974), p. 17; and Cresap, McCormick and Paget, Inc. (1974), p. III-22.
[25]Strobel (1982), p. 331.
[26]Lancaster and Teske (1973), pp. 113-114.
[27]Profet (1973), pp. 78-80.
[28]Ibid., pp. 27-34.
[29]Ibid., pp. 87ff.

involved in an AHS system, capabilities must include a common failure reporting system and common information systems to track components and their specifications.

3. **Maintenance planning and management**. In addition to the information reporting problem mentioned above, there were initially inadequate supplies of common parts. This resulted largely from the management's inexperience with traditional inventory stocking practice.[30] Also, because of the magnitude of initial system bugs, resources were not managed effectively. Because of the extremely great need to keep rolling stock on the rails, resources were funneled into crisis management, detracting from detailed trouble-shooting or other preventive maintenance practices.[31] During one maintenance audit, the ratio of hours spent on unscheduled versus scheduled maintenance was 1.48 to 1.[32] As a result, problems were not adequately diagnosed, and cars would return to the shops frequently, often with the same problem as a previous visit.

   Recommendation: Again, a maintenance function should be included early in the AHS development process. The provision and maintenance of in-vehicle components will obviously be the responsibility of equipment suppliers; these suppliers should carefully consider maintenance requirements in designing and developing these systems. Infrastructure providers should also beginning planning for maintenance requirements during the development process. In both cases, requirements will include maintenance equipment to identify and repair failures, common information systems, and clearly-defined procedures for addressing scheduled and unscheduled maintenance needs.

3.2 Non-technical Issues

The success or failure of large public transportation projects such as BART is typically driven not by the level of technical sophistication but rather by the non-technical issues. The political conditions and overall public perception of the project may have significant ramifications for its success. Because of the (often) large investment of public moneys in a project, politicians and the public alike have a vested interest in the project's outcome. The challenge to the project planners and developers is to deal with these interests appropriately. From the BART experience, it seems that if the public and political concerns for the project are not handled appropriately, the project faces an uphill battle.

In public transit projects, the loss of confidence either in the political realm or among the public at large rarely results in the full project being canceled or scrapped. In the BART case, although mistakes were made in the development process and in the early years of operation, the system operation and ridership continue to improve. This ability to tolerate short-term problems for more longer-term benefits has resulted in part from the long-term success of rail systems in other cities (Boston, New York, Chicago, Philadelphia, Cleveland, etc.). Moreover, this view of rail transit projects has led to the planning and development of other rail projects since BART. For AHS, however, no such long-term experience with the technology exists, and the early years of AHS implementation will be critical to the acceptance of this technology. For this reason, alleviating the early political and public acceptance issues will be important to sustain continued development of AHS.

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[30]Cresap, McCormick and Paget, Inc. (1974), pp. III-40ff.
[31]Ibid., pp. III-24ff.
[32]Lancaster and Teske (1973), p. 4.

3.2.1 Political Pressure

The political stakes in BART that surfaced very strongly in the early 1970's were the culmination of a political process that began more than 20 years earlier. The genesis and development of BART was the result of strong political forces in the Bay Area in the 1950's. At that time, the politicians and business community supported a proposed rail system to solve the region's problems of urban sprawl, decentralized development, and increasing traffic congestion. BART served as the core element of the regional planning program.[33] From the very outset, the political forces were sold on rather unrealistic expectations of what the rail system might do for the Bay Area.[34]

The resulting political energy was compounded by the number of actors involved. Interests included local, state and federal officials and agencies:

- Local elected officials
- The BARTD board of directors
- Regional planning commissions, including the Bay Area Rapid Transit Commission (1951-1957) and the Metropolitan Transportation Commission (since 1970)
- The California state legislature
- The federal Department of Housing and Urban Development, or HUD
- The Urban Mass Transportation Administration, or UMTA

The state of California authorized legislation creating BARTD in 1957 and provided some funding for the project through the 1960's, while HUD and UMTA provided funding for the BART system development in the late 1960's and early 1970's. Thus, a large number of political interests had a financial and / or political stake in the success of BART.

As with most public works projects, delays ended up being considerable. The initial starting date was pushed back from 1969 to 1972, and the Transbay Tube was not opened for revenue service until 1974. Delays occurred often in the late 1960's, primarily related to the final systems design, procurement and funding.[35] Yet, technical concerns and procurement problems with the ATC system and the cars contributed to much of the delay in the early 1970's.[36] Because of these delays, political pressures mounted to bring the system into revenue service as quickly as possible.

The high level of political expectations, the large number of players, and the inevitable project delays all resulted in great political pressure on BARTD and PBTB. Several researchers have suggested some measures which may have either contributed to or alleviated some of this political pressure.

1. **Interaction of technical and political forces in the development process**. During the final two years before deployment, delays in opening the system largely resulted from technical problems and debugging of delivered systems. Most researchers believe that there was insufficient time to work out these technical bugs before BART entered revenue service. Unfortunately, the technical personnel on the project (primarily at PBTB) either were not in a position to influence decision-making or simply did not speak strongly enough for a longer testing period. It seems that there was inadequate representation of technical concerns in the

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[33]Webber (1976), pp. 3-5, and Office of Technology Assessment (1976a), pp. 10-11.
[34]Webber (1976), pp. 7ff.
[35]Office of Technology Assessment (1976a), pp. 21-22.
[36]Legislative Analyst (1972), p. 12.

political process, which is largely attributed to the poor management of technical issues at BARTD.[37]

Recommendation: Technical personnel should maintain high visibility in AHS decision-making throughout the development process. Administrative and management boards should include staff with a high degree of technical competence in AHS.

2. **Ability to develop the system incrementally**. One advantage of the radial nature of the BART system design is that it permitted incremental deployment. In particular, it was not necessary to have all the lines open simultaneously, but rather lines could be added incrementally. BARTD was able to open the Fremont-Oakland line first in September of 1972, alleviating at least some of the pressure to bring the system on line. This also allowed other lines to incorporate the operating experience on the Fremont-Oakland line before they opened for revenue service. Political pressure was obviously greatest to open the Transbay Tube connection from Oakland to San Francisco;[38] unfortunately, that section was the last to open, in September of 1974.

   Recommendation: As much as system design will allow, AHS projects should take advantage of incremental deployment. This may imply that an automated highway be deployed in a small corridor initially, allowing for system expansion to other corridors in the near future. The selection of an initial corridor should be based at least in part on the ability of that corridor to demonstrate significant first user benefits.

3.2.2 Loss of Public Confidence

For a number of reasons, public confidence in BART was shaken, especially during the first few years of revenue service. From the seemingly strong voter support in 1962, the public opinion on BART deteriorated. In early revenue service, passengers found the stations difficult to get to and encountered frequent delays and disruptions in service. These service problems were compounded by the state legislature's discovery of widespread system safety and reliability problems following the first accident, a mere three weeks after beginning revenue service.[39] Today, after almost 20 years in full operation, BART ridership is just reaching the level initially predicted for 1975.

In hindsight, there seem to be a number of factors which contributed to the deterioration of public support for BART, at least in the early years of operation.

1. **Level of public interaction before opening**. Following the voters' approval of the bond bill in 1962, the level of contact between BARTD and the public diminished rapidly. This is partly due to the obvious shift in focus toward design and construction and away from political and public consensus-building.[40] However, as part of the BART legislation, communities could hold public hearings at any time after the vote; sadly, few communities took advantage of these hearings, except where there was considerable opposition to site development plans (e.g., in Berkeley[41]). Moreover, the responsibility for managing the public relations was passed from BARTD to PBTB, despite the fact that the consortium had little expertise in this area.[42] At the

[37]Burck (1975), pp. 106-107.
[38]See, for example, the emphasis in the Legislative Analyst (1972), pp. 12-13.
[39]The investigation is reported in the Legislative Analyst (1972).
[40]Zwerling (1974), p. 49.
[41]The Berkeley experience is summarized in Zwerling (1974), pp. 56-65.
[42]Zwerling (1974), p. 43; and Office of Technology Assessment (1976a), p. 22.

same time, little effort was made by PBTB to solicit public comment on the project during design and construction, for fear that this would contribute additional delays and costs.[43]

Recommendation: AHS project development should include mandatory public forums to discuss system implementation, both before initial project authorization and during the project design and construction. In addition, other public information strategies should be implemented, such as local site offices, information telephone lines, and other avenues for both public information and input.

2. **Public perception of the ease of use**. From the initial system design, it was clear that access to BART would be difficult, due to the large inter-station spacing. The system needed substantial in-station parking and considerable feeder bus service to provide station access for both drivers and transit-dependent passengers.[44] Parking facilities were and remain inadequate to handle demand. Moreover, for the feeder bus service, BART was largely unable to coordinate services with local providers such as AC Transit in the East Bay and Muni in San Francisco. While there were clearly stated policies regarding the level of service coordination between BART and these transit providers, little actually changed once BART opened for service.[45] For example, BART is still competing with AC Transit for passengers traveling across the Bay. The problems noted here may have resulted in part because BARTD was not responsible to any regional transportation planning body during development in the 1960's.[46]

   Recommendation: AHS should be incorporated in a regional transportation planning process (likely to be mandated under current federal legislation). Specifically, adverse and beneficial impacts of an AHS should be addressed in the context of the entire regional transportation system. System development should be approved by the regional planning organization and should be coordinated with other regional transportation system improvements.

3. **Overcoming early problems**. Finally, BARTD officials were not candid with the public about early problems on the system. Since much of the technical system debugging actually occurred in revenue service, there were a lot of delays and disruptions. Statistics compiled in 1979 indicated that equipment failures alone resulted in about 7 failures per day, where a failure resulted in train off-loads, unscheduled train removals, and / or schedule delays over 10 minutes.[47] In addition, BARTD had significant financial problems in its first several years of operation, as revenues were unable to cover operating costs as expected.[48] From the point of view of several researchers, the first General Manager of BARTD had difficulty admitting publicly the scope of technical and financial problems within the system. As a result, the public (and the media) tended to control the investigation of these problems, rather than personnel at BARTD.[49] Although there were substantial changes in management policies within two to three years after the system opened, the more gradual changes in public attitudes about BART are due to considerable patience of the public during the first several years of operation.[50]

   Recommendation: As much as politically feasible, problems with AHS development and implementation should be addressed candidly, both internally within the organization and externally with the public.

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[43]Zwerling (1974), p. 49; and Office of Technology Assessment (1976a), p. 45.
[44]Webber (1976), pp. 33-34.
[45]The relationship of BARTD and AC Transit is discussed in great detail by Zwerling (1974), pp. 91-104.
[46]Office of Technology Assessment (1976a), p. 45.
[47]Brumberger (1980), p. IV-13.
[48]Legislative Analyst (1974), pp. 24ff.
[49]Burck (1975), p. 164. One obvious example is the investigation by the Legislative Analyst (1974).
[50]Webber (1976), pp. 37-38.

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